Optical probing of a laser-driven electron accelerator


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Laser Wake Field Acceleration:
\[ \text{→ light intensities} \gtrsim 10^{18} \text{ W/cm}^2 \]

Bubble/ Blowout regime:
\[ \text{→ acceleration field} \gtrsim 100 \text{ GV/m} \]

Electron bunch energy:
typically \( E = 200 \text{ MeV} - 1.5 \text{ GeV} \)

Electron bunch duration:
O. Lundh, et al. Nature Physics 7, 219 (2011) \( \tau_p = (4,4) \text{ fs} \)
A. Buck, et al. Nature Physics 7, 543 (2011) \( \tau_p = (5,8\pm 2.1) \text{ fs} \)

Transverse electron bunch size:
M. Schnell, et al. Phys. Rev. Lett. 108, 075001 (2012) \( < (1,6\pm 0,3) \mu m \)
Plateau, et al. Phys. Rev. Lett. 109, 064802 (2012) \textit{ca.} 0.1 \mu m
**Probing laser wakefield accelerators**

**Challenge:** Imaging a tiny, fast moving object.

- characteristic length scale: \( \lambda_p = \frac{2\pi c}{\omega_p} \)
- sufficient probe bandwidth
- group velocity of driver: \( \sim c \)

- time integrated
- for slowly evolving plasma features
  - Fourier Domain Holography, ...

- snap shots: \( \tau_{probe} \ll \lambda_p/c \)
- for fast evolving plasma features
  - Interferometry, Shadowgraphy, Polarimetry, ...

• longitudinal

• transversal
Split off part of the compressed main pulse, chirp it and let it co-propagate.
Temporal resolution depends on probe pulse bandwidth: \[ \tau_{\text{probe}} \cdot c > \frac{\lambda_p}{2} \]
Transverse probing

pump pulse
imaging lens
probe pulse
super sonic gas jet
electrons xrays,...
Light Wave Synthesizer -20

Sub-10-fs, multi-Terawatt optical parametric chirped pulse amplifier
parameters:

\[ E_{\text{laser}} = 65 \text{ mJ}, \quad \tau_{\text{laser}} = 8.5 \text{ fs}, \]

\[ f/6 \text{ OAP}, \quad I_{\text{laser}} = 6 \times 10^{18} \text{ W/cm}^2 \]

probe pulse:

\[ \tau_{\text{probe}} = 8.5 \text{ fs @ 1}\omega, \quad 2\mu\text{m imaging resolution} \]

A. Buck et al., Nature Physics 7, 543–548 (2011)
LWS 20 shadowgraphy - sub 9fs probe

Shadowgraphy
visualize e-bunch via associated B-fields

Polarimetry
visualize e-bunch via associated B-fields

\[ \lambda_p = 2\pi c \sqrt{\frac{m_e \epsilon_0}{n_e e^2}} \]

A. Buck et al., Nature Physics 7, 543–548 (2011)
Frontend of the JETi laser

Power amplifier of the JETi laser

27 fs, 800 mJ, (30 TW peak power), $5 \times 10^{20}$ W/cm$^2$ peak intensity, 10 Hz
**Few cycle microscopy**

High resolution imaging system

- **Achromatic Doublet**
  - focal length: 250 mm

- **10x Mitutoyo Plan Apo NIR Infinity-Corrected Objective**
  - focal length: 20 mm
  - long working distance: 30 mm
  - resolving power: 1.5 µm

- **Magnification factor:** 12.5
- **CCD pixel size:** 6.4 µm
Few cycle probe beam - setup

99:1 beamsplitter

800 mJ / 27 fs

compression ≈30 fs with chirped mirrors

neon/ argon filled hollow core fiber

In: 500 µJ
Out: 300 µJ

chirped mirrors for pulse compression

Few cycle probe beam - characterization

Argon @ 0.4 bar
Fourier limit: 4.4 fs

τ = 5.5 fs

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Few cycle probe beam - optimization

Stereo ATI Phasemeter to measure the asymmetry of the laser pulse


3600 subsequent shots (1h), > 86 % of shots below 4 fs

D. Adolph et al., in preparation
**Experimental parameters**

**JETi 40**
35 fs, 720 mJ (24TW) laser pulse
f/13, $d_{(\text{FWHM})}$: 11 µm, $a_0 \approx 1.7$

- Supersonic gas jet (2.7 mm)
- Few cycle, NIR probe beam for shadowgraphy
- Scintillator screen (pointing & divergence)
- Dipole magnet
- Scintillator screen

3 MeV – 1.0 GeV
Energy resolution better 2%

*developed in cooperation with group of Axel Bernhard*
LWFA under the microscope

Helium, 1.7x10^{19} cm^{-3}

a: plasma wave  
b: ionization front  
c: Raman side scattering  
d: tilted plasma wave  
e: Thomson scattering  
f: wavebreaking radiation  
g: speckle/ noise  
h: dust/ dirt
sub 9 fs vs. sub 6 fs probe pulses

A. Buck et al., Nature Physics 7, 543–548 (2011)

Shadowgram is formed mostly in the center part. High gradients & short pulse duration give high contrast.

by courtesy of Evangelos Siminos
(in preparation)
Bubble length - measurement

electron density:

computed shadowgram:

experiment:

Bubble length and plasma period length are directly accessible!
Influence of the plasma density

Results for the second plasma period

\[ \lambda_p = 2\pi c \sqrt{\frac{\gamma m_e e}{n_e e^2}} \]

\[ \frac{\alpha P}{P_c} > \frac{1}{16} \left[ \ln \left( \frac{2n_c}{3n_e} \right) - 1 \right]^3 \]

for our parameters: \( n_e > 1.5 \times 10^{19} \text{ cm}^{-3} \)

Influence of the focal spot

\[ \frac{\alpha P}{P_c} > \frac{1}{16} \left[ \ln \left( \frac{2n_c}{3n_e} \right) - 1 \right]^3 \]

effective critical Power!

\[ \alpha = 0.23 \]

JETi40 focal spot without adaptive optic

Filamentation instability: Helium, \(2 \times 10^{19} \text{ cm}^{-3}\)
Evolution of the plasma wakefield at the critical density for self-injection

![Graph showing the relationship between plasma wavelength and electron density](image-url)
Evolution of the plasma wakefield

Evolution of the plasma wakefield

Bubble expansion starts before injection.

No beamloading but amplification of the pump pulse.

\[ \lambda_p^* \approx \lambda_p \left(1 + \frac{a_0^2}{2}\right)^{1/4} \]

3D PIC simulation including the probe

- **electron density & pump intensity**
  - $n/n_0$
  - $B_2 (10^4 T)$

- **computed shadowgrams**
  - relative intensity modulation

- **experiment**
  - relative intensity modulation

3D PIC simulation (EPOCH), 150x70x70 $\mu m^3$ sliding box
2700x525x525 cells

by courtesy of Evangelos Siminos
Bubble expansion – simulation

Bubble expansion starts before injection.

No beamloading but amplification of the pump pulse.

Stable LWFA – Ionization injection

Beam pointing gas jet selfinjection

optimized laser focal spot (adaptive optic)

Gas cell

Beam pointing gas cell 95% He+ 5% N₂

\[ n_e = 1 \times 10^{19} \text{ cm}^{-3} \]
Excitation of asymmetric plasma waves

Stimulated side scattering
Transition from linear to nonlinear regime

\[ v_g t = 390 \, \mu m \]
\[ n_e = 1.65 \times 10^{19} \, cm^{-3} \]

\[ v_g t = 520 \, \mu m \]

\[ v_g t = 590 \, \mu m \]

Pulse front tilt & mismatch  
Pump amplification & wavefront rotation  
Blowout
Laser hosing instability

spatial temporal asymmetry

\[ n_e = 1.65 \times 10^{19} \text{ cm}^{-3} \]

\[ n_e = 2.1 \times 10^{19} \text{ cm}^{-3} \]

Laser hosing instability - evolution

spatial temporal asymmetry
- Important at long interaction length


\[ n_e = 2.2 \times 10^{19} \text{ cm}^{-3}, \Delta \tau = +6.6 \text{ ps} \]
- *Few cycle microscopy* is a very powerful diagnostic tool for (laser) plasma interactions

- *Few cycle microscopy* reveals the transformation of the plasma wave during formation, injection and acceleration

- Experimental observation of bubble expansion in the self-injection regime leading to injection of electrons into the wakefield

- Benchmark PIC codes by investigating instabilities

Very interesting times ahead!
Probing future wakefield accelerators

Energy gain

\[ \Delta E [GeV] \approx 1.7 \left( \frac{P[TW]}{100} \right)^{1/3} \left( \frac{10^{18}}{n_p [cm^{-3}]} \right)^{2/3} \left( \frac{0.8}{\lambda_0 [\mu m]} \right)^{4/3} \]


For probing techniques, the refractive index defines the sensitivity!

\[ n = \sqrt{1 - \frac{\omega_p^2}{\gamma \omega_{probe}^2}} \]

lower plasma density

\[ \lambda_p = 750 \text{ nm} \]

lower plasma frequency

**JETi 200**: \( P = 200 \text{ TW}, \quad \tau_L = 17 \text{ fs} \)

\[ \lambda_p = 1.4 \mu m \]

pulse duration: \( \tau_L \leq \lambda_p / 2 \)

\[ n_p = 1.6 \times 10^{19} \text{ cm}^{-3} \]

\[ n_p = 0.4 \times 10^{19} \text{ cm}^{-3} \]
Few cycle light sources in the MIR

\[ n_e = 7 \cdot 10^{18} \text{ cm}^{-3} \]

\[ \lambda_{probe} = 750 \text{ nm} \]

Sub 3-cycle laser pulses @ \( \lambda_c = 3.1 \mu m \)

\[ E_{\text{pulse}} = 10 \mu J @ 160 \text{ kHz} \]

M. Hemmer et al. Optics Express 21, 28095 (2013)

Super continuum @ \( \lambda_c = 6.5 \mu m \)

\[ E_{\text{pulse}} = 100 \text{ nJ} @ 1 \text{ kHz} \]

C.R. Petersen et al. Nat. Photon. 8, 830 (2014)

All optical techniques like shadowgraphy (imaging wakefields), polarimetry (imaging magnetic fields) are feasible for PWFA experiments!
Thanks to all collaborators


E. Siminos

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